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A 1-Watt, 6-Gigahertz IMPATT Amplifier for Short-Haul Radio Applications

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A 1-watt IMPATT diode amplifier has been developed for short-haul FM radio relay applications in the 6-GHz common-carrier band. The amplifier is used in the new TM-2 system and as part of a retrofit package to upgrade the performance of the existing TM-1 system. Amplification is provided by a single silicon IMPATT diode which is used in an injection-locked mode. A finned heat sink provides IMPATT diode cooling by natural air convection within the radio bay. The diode is expected to have a mean life greater than 10 years, and it can be replaced in the field without the use of special tools or equipment. This microwave-integrated amplifier contains the rf samplers and detectors necessary to monitor both input and output rf power levels. The input power monitor also provides an input to a power-supply squelch circuit that removes dc power from the IMPATT diode if the rf input signal level becomes too low for adequate performance. The influence of the system requirements upon the amplifier design is described, and data on system performance are presented.

I. INTRODUCTION

The IMPATT diode has been developed to the point where several watts of cw power can be generated reliably in the microwave frequency range. This negative-resistance device used in conjunction with a circulator comprises a reflection amplifier suitable as the power amplifier in a microwave communications transmitter. In the present application, the diode operates in the injection-locked oscillator mode. It was demonstrated by Tatsuguchi, Dietrich, and Swan that such an amplifier using a single silicon IMPATT diode could meet the basic performance objectives of a typical short-haul radio-relay system.[1] The amplifier operates with a nominal gain of 20 dB and a noise figure of less than 52 dB. The corresponding system performance is better than 22 dBrnc0 per hop for a 1200-circuit message load. The amplifier's system performance is found to be dominated by thermal noise, with intermodulation distortion negligible. The dc-to-rf efficiency is 4 percent.

To be useful to the system, the amplifier package also contains rf samplers and detectors necessary to monitor the rf input and output power levels. The input power-monitor circuit furnishes the input information for a power-supply squelch circuit. If the input rf level drops low enough so that the locking handwidth of the amplifier hecomes small, the power supply is turned off, preventing the IMPATT oscillator from free-running out of the assigned frequency range. The dc power is automatically restored when the input rf level returns to normal. The amplifier also contains harmonic suppression filters to prevent radiation of spurious tones. The amplifier has standard WR-159 waveguide input and output ports with VSWRs of less than 1.07 across the hand.

To he suitahle for manufacture, an economical design was evolved hased on the microwave integrated-circuit techniques successfully employed in the TH-3 system hy Dietrich.[2] The construction consists of a thin-film strip-line pattern on a suspended alumina suhstrate, which is mounted in a die-cast aluminum housing, connected to a coaxial section containing the IMPATT diode, the tuning mechanism, and a second harmonic filter. In addition, a wide range of tunahility had to he incorporated to accommodate a wide range of diode parameters, hoth for initial manufacture and field replacement of the diode. Both frequency and output power adjustments are provided. All these features have heen successfully accomplished in the amplifier designed for manufacture.

II. AMPLIFIER DESIGN

The amplifier design is hased upon the use of a single silicon IMPATT diode used in a phase-locked oscillator mode. This mode of operation, descrihed helow, is chosen since it permits the relatively high gain of approximately 20 dB to he ohtained stahly in a single stage.

2.1 Operating point selection

The choice of an operating point for the amplifier follows the method descrihed by Tatsuguchi et al.[1] Figure 1 illustrates typical contours of constant system thermal noise performance, in dBrnc0 per hop, plotted on coordinates of amplifier output power versus amplifier noise figure. The system performance contours shown apply to the highest frequency message slot of one particular short-haul FM system configuration that is operated at a 1200-message circuit loading. The contours assume that a +10-dBm level signal is available to drive the amplifier. This input power level is the minimum value anticipated in one of the systems in which this amplifier will be used. The options open to the amplifier circuit designer are illustrated on the same figure

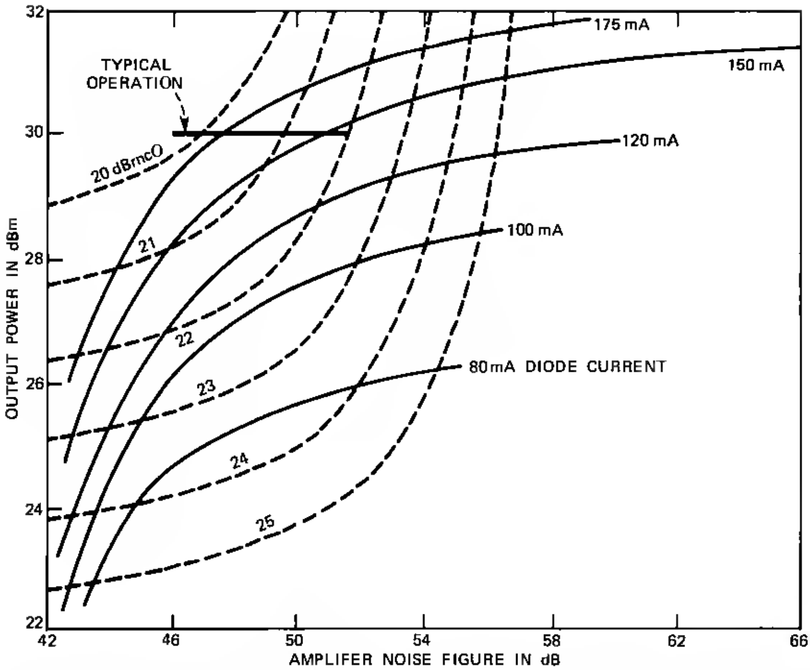

Fig. 1—Contours of constant system thermal-noise performance, in dBrnc0 per hop, plotted on coordinates of amplifier output power versus amplifier noise figure. A particular amplifier's performance is indicated by the solid lines at several IMPATT diode dc currents. Typical performance obtained on a large sample of amplifiers when adjusted for 1-watt output power is shown.

by tbe superimposed contours of IMPATT amplifier performance at various dc power levels. For a given dc power level, the operating point is a function of the microwave circuit impedance seen hy the IMPATT device. The shape of these curves is due to the fact that an IMPATT device becomes noisier as the rf level is increased. From such curves, it hecomes apparent that operation at the maximum possible rf power will result in poor system performance. Optimum performance occurs at neither maximum rf power nor minimum noise. It is instructive to note that the optimum performance, i.e., lowest dBrnc0 number, occurs with the largest dc power. The use of high dc powers must be tempered hy reliahility considerations, which generally dictate the use of lower powers.

For this amplifier application, the trade-off between rf output power, FM noise, and diode reliability formed the basis of the decision to operate at 1-watt rf output with 24 watts of dc supplied to the IMPATT diode. At this operating point, the diode junction temperature is expected to he approximately 200°C in convection-cooled radio bays

operating in room ambient temperature up to 50°C. This operating point is expected to provide a mean diode life greater than 10 years. This reliability is the result of careful device processing combined with low thermal impedances both within the diode package and between the diode case and ambient air.

2.2 Oscillator mode

The IMPATT diode is operated in an injection-locked (phase-locked) oscillator mode, shown schematically in Fig. 2. The IMPATT device and its associated resonating circuitry terminate one port of a circulator in a negative impedance. In the absence of an input signal, a free-running oscillation at frequency f_0 occurs, which is coupled to the output through the circulator. When an appropriate input signal is added, the oscillation frequency locks to the input over a band of frequencies $2\Delta f$, approximately symmetrical about f_0. The free-running frequency is adjusted to the desired operating channel. Figure 2 illustrates the power and phase variations that occur across the locking frequency band. The power levels and oscillator external Q (Q_{ex}) are chosen such that Δf is at least 10 times the highest modulating frequency. In this way, only the center linear portion of the phase variation curve is used, and phase distortion is minimized.

Since the rf output power is fixed from other considerations (system performance and fading margin) and the rf input power available in

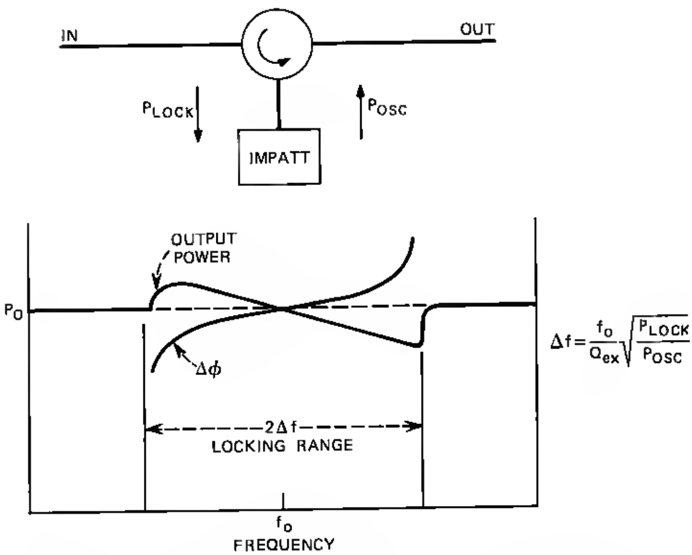

Fig. 2—Simplified representation of an injection-locked oscillator.

the systems in which the amplifier is to be used is limited, the designer is required to provide a circuit of the lowest possible Q. For this amplifier, a low Q circuit is provided by the use of a diode circuit consisting of a coaxial one-quarter-wavelength transformer plus a short section of coaxial line between the transformer and the diode that series-tunes the IMPATT diode's capacitance. With this resonator, the circuit Q is sufficiently low that Q_{ex} is largely determined by the IMPATT device itself.

2.3 IMPATT characteristics

The IMPATT diode used for this amplifier is an n-type silicon diode whose junction side is bonded to a metallized diamond within a copper and ceramic microwave pill package.[3] The large-signal rf characteristics of the diodes are measured near 6 GHz using the method described by Decker et al.[4] The diode wafer admittance is measured on all devices at 24-watts dc, with an rf voltage corresponding to the diode's operating point in the amplifier. Wafer susceptances are specified at 19.0 millimhos. Tuning is provided to accommodate a range of diode susceptances. The wafer Q, defined as the magnitude of the ratio of wafer susceptance to wafer conductance, has values that vary by a factor of 2.5 to 1.

2.4 Circuit description

The requirements of practical radio-relay equipment dictate an amplifier circuit somewhat more complex than the simple circulator, diode, and resonator shown in Fig. 2. A more complete schematic of the amplifier is shown in Fig. 3. The circuit contains three circulators, of which the center circulator corresponds to the one shown in Fig. 2. Additional circulators with one port resistively terminated are used at both the amplifier's input and output to provide isolation from the effects of external reflections and to provide input and output return losses better than 30 dB.

The dc power for the IMPATT diode from the current-regulated power supply is coupled to the oscillator port of the center circulator through a resistor and a band-stop filter tuned to 6 GHz. The resistor is used here to provide the high resistive impedance at low frequencies that has been shown by Brackett to prevent spurious oscillations.[5] The dc power is isolated from the remaining rf circuit by a series capacitor in the main rf circuit adjacent to the band-stop bias filter.

On the output side of the center circulator, a small sample of the amplified output is picked off by a nondirectional coupling probe. This sample of the rf output is detected using a point contact diode

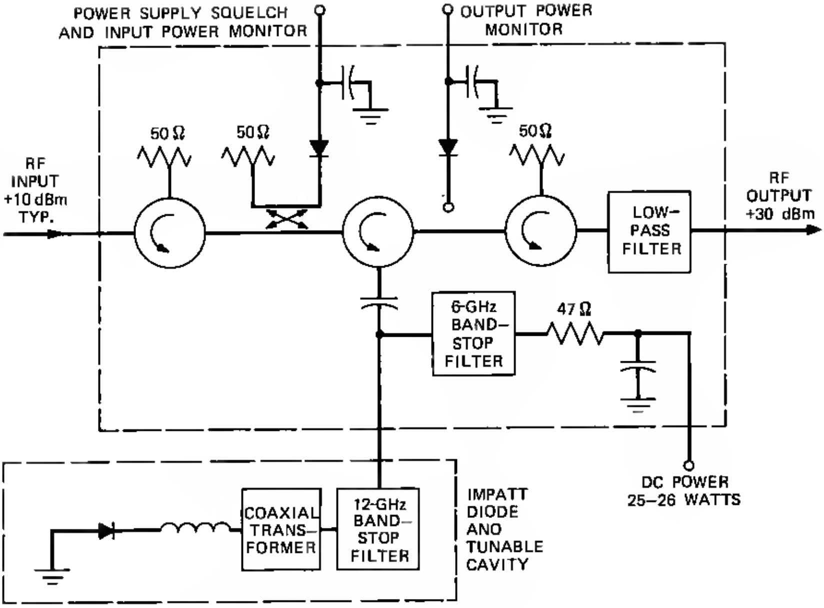

Fig. 3—Schematic diagram of complete IMPATT diode amplifier.

to provide a dc current for the radio bay meter panel and alarm functions.

On the input side of the center circulator, a sample of the input power is taken and detected for bay panel metering and to operate a power-supply squelch circuit. Tbe power-supply squelcb operates to remove dc power from the IMPATT diode if tbe rf input to tbe amplifier falls below a prescribed level. Tbis effectively prevents free-running oscillations by tbe IMPATT oscillator, wbose free-running frequency is not sufficiently stabilized to prevent interchannel interference. A directional coupler is used for the input coupler to provide a good matcb on the circulator common-arm and to provide, via its 20-dB directivity, discrimination against leakage of power generated by tbe IMPATT diode.

A band-stop filter is used on tbe oscillator port of tbe center circulator to prevent second-barmonic energy generated by the IMPATT from interfering with the operation of tbe monitor circuits. A low-pass filter is located at tbe amplifier's output to ensure tbat all barmonics are suppressed.

III. CIRCUIT FABRICATION AND TUNING

Most of the circuit is fabricated using the microwave integrated-circuit techniques developed for use in the TH-3 system.[2] Film inte-

grated circuits (FICS) consisting of patterns defined photolithographically on 0.024-inch (0.61-mm) thick unglazed alumina are used as a suspended-substrate strip-line transmission-line medium. The strip-line circuitry, as well as the amplifier's waveguide input and output, are contained in a die-cast aluminum housing, shown in the amplifier photograph, Fig. 4. The IMPATT diode and its resonator are contained in a short section of coaxial line that projects perpendicularly from the housing and is topped by the large, finned heat sink used for IMPATT diode cooling. Adjustments are provided on the coaxial section for field tuning of frequency and power output.

3.1 Strip-line circuits

The layout of the circuitry within the die-cast housing is illustrated in Fig. 5 and shown pictorially in Fig. 6. The ceramic suhstrates are located within a narrow channel to avoid multimoding prohlems. The complex suhstrate shape is fahricated hy an automated laser-cutting

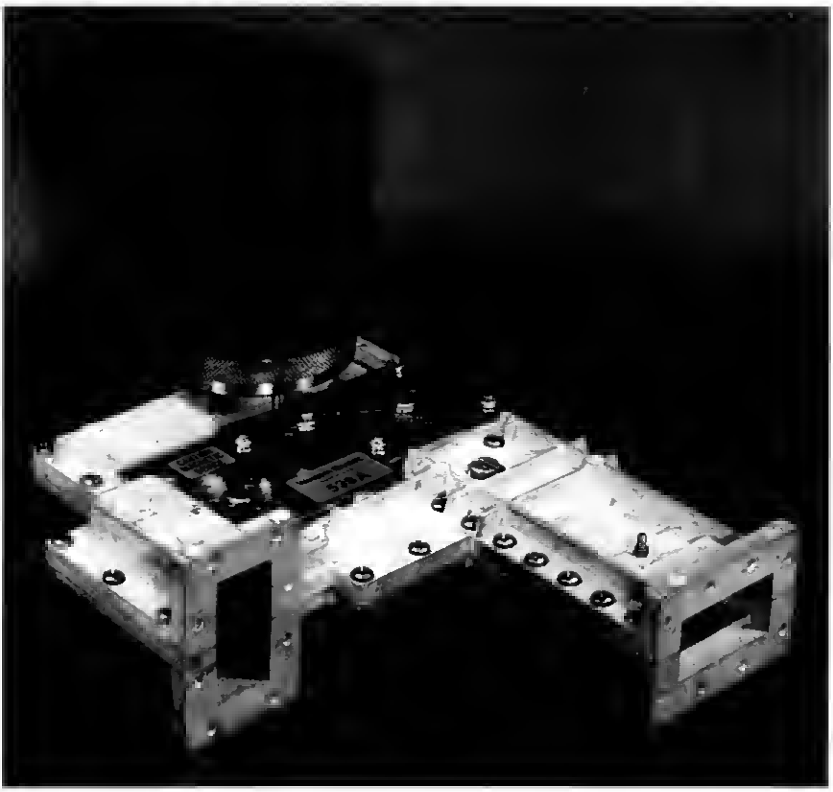

Fig. 4—Complete amplifier.

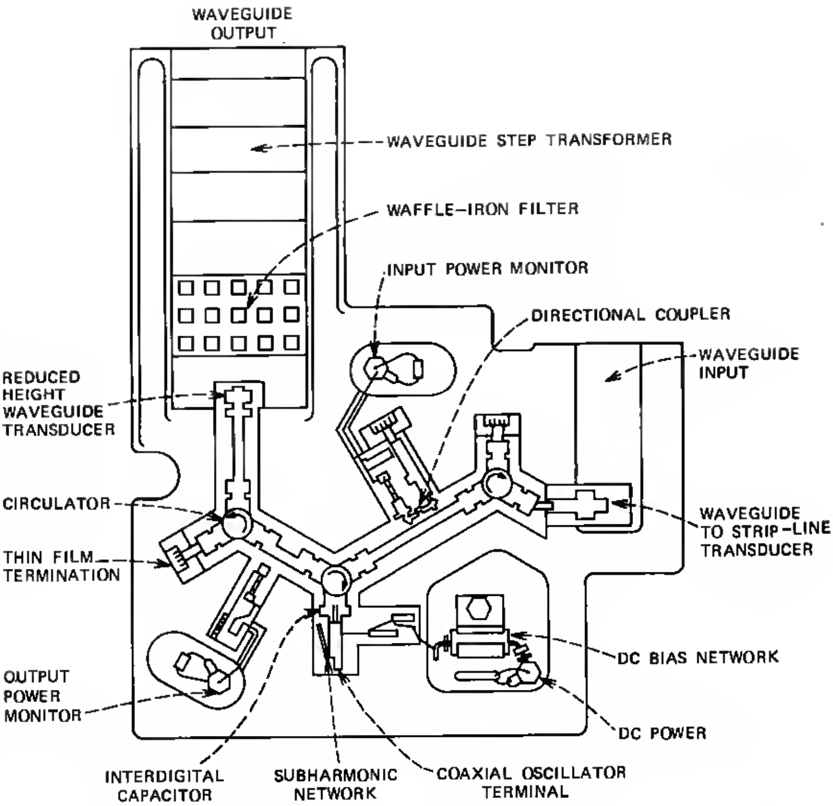

Fig. 5—Arrangement of waveguide and strip-line circuit within die-cast housing.

technique.[6] The amplifier's full-height waveguide input is shown on the right. A thin-film prohe transition from the input waveguide to the suspended-suhstrate strip-line couples the input signal to the first of the three circulators. This circulator, with one port terminated in a thin-film resistor, provides the necessary input isolation. The circulator and termination designs follow closely those descrihed hy Dietrich,[2] modified to improve the temperature stahility. A directional coupler, located hetween the input and center circulators, diverts approximately 10 percent of the input rf signal to the input detector diode to generate the dc needed for hay panel metering and power-supply squelch functions.

The remaining input signal is coupled to the oscillator port of the center circulator. The series capacitor, which dc-isolates this port, is realized hy a narrow, meandering, interdigital gap in the thin-film conductor. The 6-GHz hand-stop hias filter is realized hy a high-

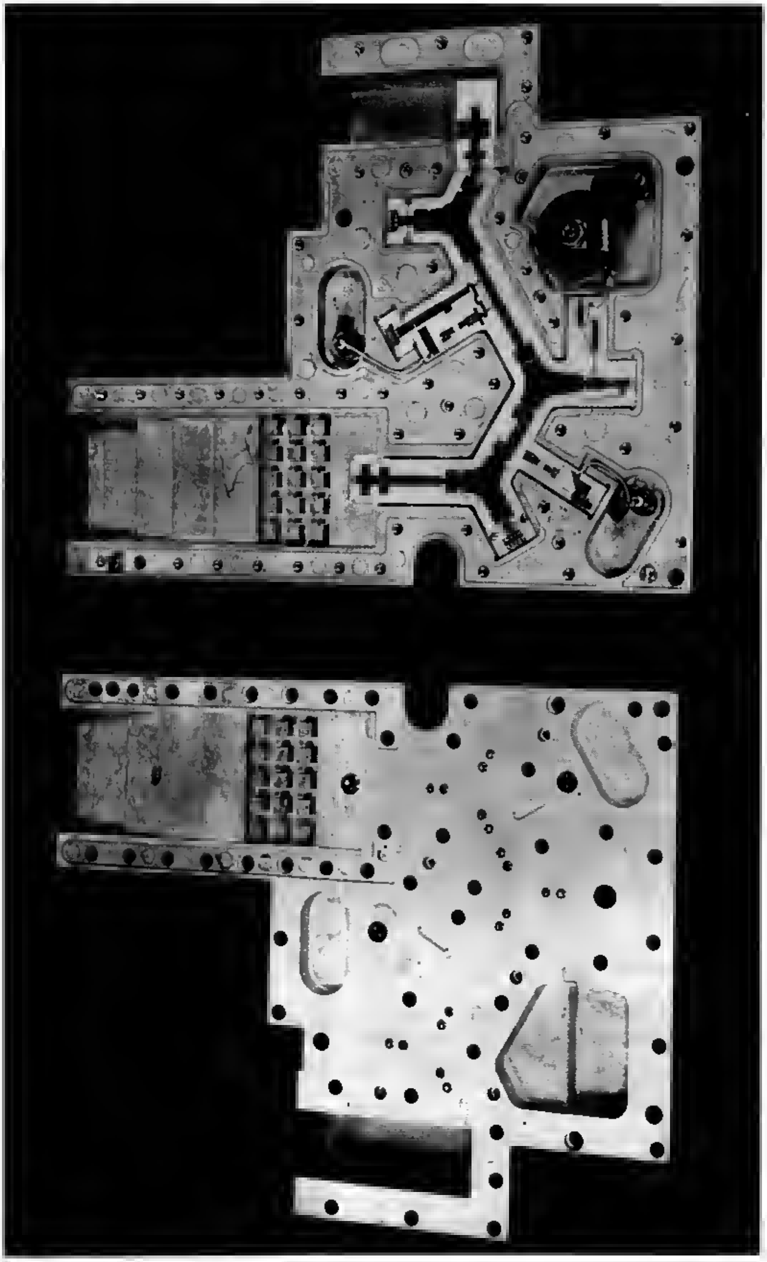

Fig. 6—Pictorial view of open die-casting showing strip-line circuitry.

characteristic-impedance line along which, at quarter-wavelength intervals, are placed two quarter-wavelength-long open-circuited stubs of lower characteristic impedance. The hias circuit is completed hy a 47-ohm power resistor that is clamped to the aluminum housing to maximize heat transfer. Several ferrite heads are placed on the leads of this resistor to provide additional stability against bias circuit oscillations.

An open-circuited stuh, one-half-wavelength long at 6 GHz, which connects to the oscillator terminal through a thin-film resistor, is used to control the circuit impedance at 3 GHz (the suhharmonic of the 6-GHz hand) without adding significant loss or mismatch at 6 GHz.[7] This was found to be necessary to eliminate frequency jumps during tuning, which occur when the suhharmonic impedance is too high.

At the end of the thin-film pattern (coaxial oscillator terminal), connection is made, using a hellows, to the center conductor of the coaxial line through the top half of the aluminum housing.

The amplified rf signal reflected from the IMPATT diode down the coaxial line is coupled hy the center circulator to the output circulator. A small portion of the amplified output is capacitively coupled to the output detector circuit to provide the direct current for hay panel metering and alarm functions. This nondirectional coupling is approximately 28 dB. The amplified signal passes through the output circulator, used as an isolator, and is coupled into a reduced-height waveguide. Within the reduced-height waveguide, a waffle-iron filter[8] having a low-pass characteristic strips the amplified signal of any residual harmonic energy either generated hy the IMPATT or contained in the input signal. Following the waffle-iron filter, a four-step transition couples the reduced-height waveguide to standard-height WR-159 waveguide.

3.2 Coaxial circuit

A cross section of the coaxial line is shown in Fig. 7. At the hottom, just above the bellows contact to the thin-film circuit, is located a three-resonator, radial-line, hand-stop filter[9] that is tuned to the 12-GHz second harmonic of the 6-GHz common-carrier hand. The filter prevents the second harmonic energy generated by the IMPATT diode from causing anomalous monitor circuit operation. Appropriate steps in the coaxial center conductor in the filter section provide a good match across the 6-GHz hand. The center conductor tip is spring-loaded against the IMPATT diode, which is held centered at the upper end of the coaxial section. A large, finned heat sink contacting

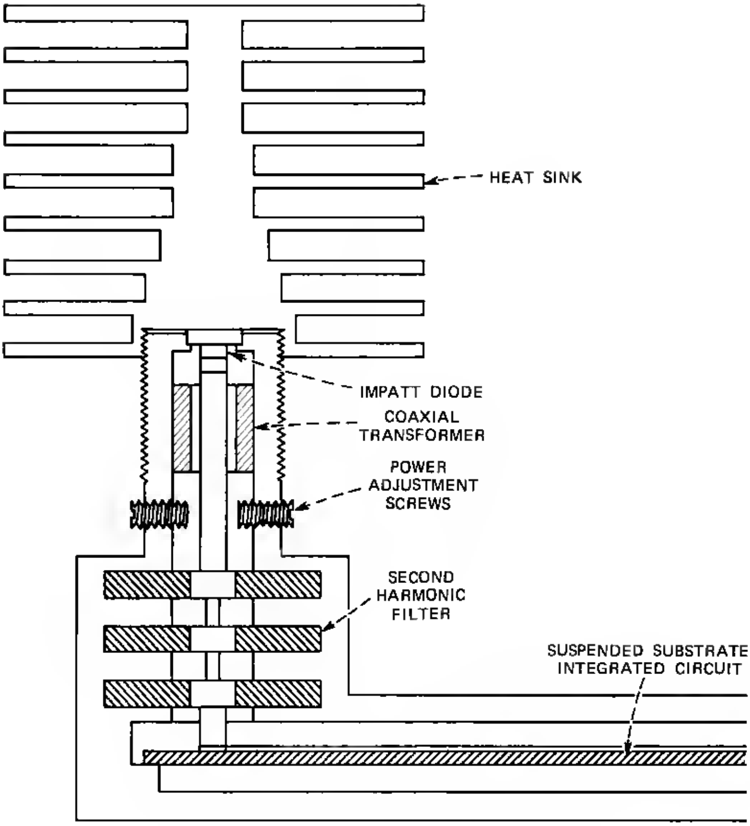

Fig. 7—Cross section of the coaxial line section.

the back of the diode provides diode cooling and eliminates the need for forced convection.

IMPATT tuning is accomplished by a movable quarter-wavelength coaxial transformer and four capacitive power-adjustment screws located radially around the coaxial line at a point nominally an eighth-wavelength from the end of the transformer. The position of the transformer relative to the IMPATT diode primarily determines the frequency of operation. The transformer is moved using a large-diameter knurled ring, shown just below the heat sink in Fig. 4. This ring is mechanically coupled to the transformer through two slots in the coaxial line. These slots are completely covered by the transformer and ring to prevent rf leakage.

The transformer section characteristic impedance is designed to produce 1 watt at the amplifier's output port (nearly 1 dB more at the

diode's location) with the highest Q diode and with the power adjustment screws adjusted flush with the inner diameter of the coaxial outer conductor. For all other diodes that would give greater than 1 watt with this transformer, capacitance is added using the four power-adjustment tuning screws. When transformed through the coaxial circuit to the diode position, the added capacitance appears as an increase in the resistive part of the circuit impedance. Increased circuit resistance reduces the generated power down to the 1-watt level, where optimum system performance occurs. This power adjustment is made on diodes having low values of Q; the increase in circuit Q hecause of the screw insertion is counterhalanced hy the lower diode Q, so that the overall external Q is not increased hy this power adjustment when compared with high Q diodes requiring little screw penetration.

3.3 *Circuit tuning*

The circuitry within the die-cast housing is initially tuned in the factory with a 7-mm precision connector located in place of the IMPATT diode and heat sink. During the initial tuning, the transformer is not installed and the power-adjustment screws are adjusted flush with the coaxial-line inner surface. Tuning of all ports of the three circulators to hetter than 30-dB return loss is accomplished across the 8-percent common-carrier hand. The three ports of the center circulator are tuned over a slightly wider hand to include the extremities of the locking handwidth of amplifiers operated on the end channels of the common-carrier hand.

By matching the diode port of the center circulator to achieve this hroadhand high return loss, the oscillator circuit Q is essentially determined by that of the quarter-wavelength transformer and the short section of 50-ohm line from the transformer to the diode. In practice, Q_{ex} of the oscillator is determined largely hy the IMPATT diode wafer. The transformer position and power adjustment screws permit adjustment in the field of any amplifier to 1 watt on any channel assignment with any diode. The IMPATT diode is replaceahle in the field hy simply removing the heat sink and inserting a new diode in the coaxial line against the spring-loaded center conductor.

The amplifier cost has been kept low hy the use of thin-film integration, casting technology, and laser cutting of ceramic suhstrates.

IV. AMPLIFIER PERFORMANCE

Ten models were constructed in the lahoratory, and information was conveyed to the Western Electric Company, who is now producing the unit. Measurements of intermodulation distortion indicate that the distortion products are small and that system performance

can be accurately predicted on the basis of power output and FM thermal noise with no correction for distortion. Performance shown in Fig. 1 can be readily obtained using the silicon IMPATT diodes in manufacture. A detailed evaluation has been completed of a TM-2 system in Ohio that includes eight factory-built IMPATT amplifiers. Satisfactory operation was noted over a 10-month test period.

V. SUMMARY

A 1-watt, 6-GHz silicon IMPATT diode amplifier has been developed and is being manufactured for use as the transmitter power amplifier in short-haul radio systems. The amplifier operates with a nominal gain of 20 dB and a noise figure of less than 52 dB. The noise contribution of the IMPATT amplifier is substantially thermal noise, with intermodulation distortion negligible. The dc-to-rf efficiency is 4 percent. The amplifier includes integrated input and output rf power monitors and harmonic suppression circuitry.

The input monitor circuit furnishes the input information for the power-supply squelch circuit. If the input rf level drops low enough so that the locking bandwidth becomes small, the power supply is turned off, preventing the oscillator from free-running out of the assigned frequency range. The dc power is automatically restored when the input level returns to normal.

The low cost and reliability of this IMPATT amplifier make it an attractive rf output device in short-haul applications.

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